Simple broadband implementation of a phase contrast wavefront sensor for adaptive optics

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Abstract: The most critical element of an adaptive optics system is its wavefront sensor, which must measure the closed-loop difference between the corrected wavefront and an ideal template at high speed, in real time, over a dense sampling of the pupil. Most high-order systems have used Shack-Hartmann wavefront sensors, but a novel approach based on Zernike's phase contrast principle appears promising. In this paper we discuss a simple way to achromatize such a phase contrast wavefront sensor, using the $\pi/2$ phase difference between reflected and transmitted rays in a thin, symmetric beam splitter. We further model the response at a range of wavelengths to show that the required transverse dimension of the focal-plane phase-shifting spot, nominally λ/D, may not be very sensitive to wavelength, and so in practice additional optics to introduce wavelength-dependent transverse magnification achromatizing this spot diameter may not be required. A very simple broadband implementation of the phase contrast wavefront sensor results.

OCIS codes: (010.1080) Adaptive optics, (010.7350) Wave-front sensing, (350.1260) Astronomical optics.

References and links

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1. Introduction

The Shack-Hartmann wavefront sensor is used in most high-order adaptive optics (AO) systems. One of its advantages is broadband response, permitting the high sensitivity required for astronomical AO. Furthermore, as the number of subapertures becomes large, the Shack-Hartmann has benign error propagation characteristics during the reconstruction process compared to those of the curvature wavefront sensors, also broadband, that were used with great success in some of the earliest astronomical AO systems.

Substantial recent interest has developed in the use of Zernike's phase contrast technique [1] as a real-time wavefront sensor for adaptive optics [2-7]. Sensitivity per subaperture measurement, at least for monochromatic operation, is high [7]; error propagation during reconstruction also appears favorable, perhaps even better than that of the Shack-Hartmann [7]. To realize competitive sensitivity in practice will require achromatizing the phase contrast sensor, and some possibilities have been discussed [7]. In this paper, a novel and particularly simple way to achieve broadband response will be presented.

2. The phase contrast filter as a real-time adaptive optic wavefront sensor

The phase contrast approach was originally devised for microscopy by Zernike [1] to convert phase objects, such as transparent biological samples, into intensity objects. An adaptation for real-time adaptive optic wavefront sensing is shown schematically in Fig. 1. Light from an AO guide star may be described by a pupil field $A \cdot exp(i\varphi)$, where A is the aperture function (transmission) and φ is the phase across the telescope pupil. The phase is not normally observable in the reimaged pupil of Fig. 1: in the small-phase approximation, $exp(i\varphi) \sim 1+i\varphi$, it is 90° out of step with a large "undiffracted" component [8,9]. In the intervening focal plane, however, these undiffracted rays are spatially localized within the central $\sim\lambda/D$, where D is the pupil diameter. This localization provides a way of isolating and preferentially phase-shifting one of the two components. In particular, by inserting a spot of dielectric of roughly this diffraction-limited transverse size, the central rays may be selectively retarded by a quarter wave with respect to the higher-order, off-axis rays. The phase signal will thus be brought into step with the undiffracted signal, and become observable as a small intensity variation across the pupil superposed on a bright, uniform illumination. In the small-phase approximation, the intensity in the reimaged pupil is now proportional to $1 \pm 2\varphi$, depending on whether the focal-plane spot advances or retards the phase.

The signal fraction drops at high Strehl ratio, as less of the guide star light is contained in the phase contrast modulation. But the overall sensitivity remains comparatively high because phase is measured directly, without the geometric dilution of performance suffered when phase is inferred from measurements of phase gradients. The phase sensitivity of the Shack Hartmann in a one-axis, single-subaperture measurement is

$$\Delta\varphi_x \sim \frac{3\pi^2}{8}\frac{1}{SNR} \sim \frac{3.7}{SNR} \quad , \tag{1}$$

where SNR is the photodetection signal-to-noise ratio; the total (two-axis) error is $\sqrt{2}$ times as large [10], or $\sim 5.2/SNR$. For a phase contrast sensor, considering only shot noise for simplicity of illustration, the signal in a single subaperture sensing n photons is $2\varphi n$, while the noise is $\sqrt{n}$; the corresponding detection limit is found by equating these expressions to be [7]

$$\Delta\varphi \sim \frac{0.5}{SNR} \quad . \tag{2}$$

The true SNR is set by photon noise (shot noise) and various detector noise sources such as read noise and dark current. One advantage of the phase contrast approach is clear from Fig. 1: a single pixel of the wavefront sensor CCD is used per subaperture, compared to four by the Shack-Hartmann, so the read noise is lower. There are several other possible advantages of moderate importance that have been listed and discussed elsewhere [7].

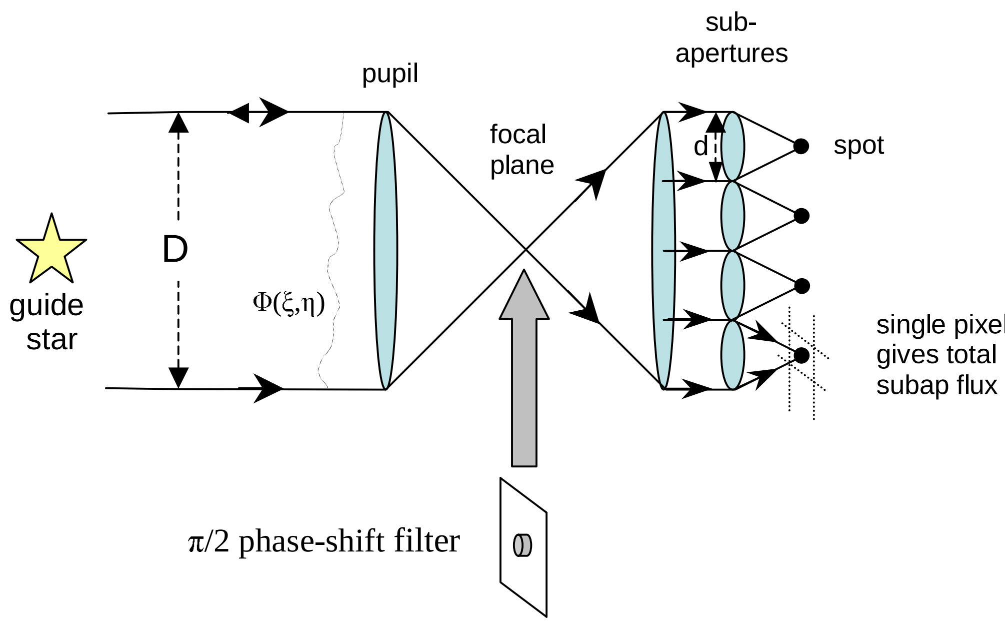

Fig. 1. Schematic of the phase contrast filter as a real-time wavefront sensor for adaptive optics. Light from an unresolved guide star enters the telescope with atmospherically-induced errors represented by a phase function across the pupil, $\varphi(\xi,\eta)$. The telescope, represented here by a single lens, brings the light to a focus on a Zernike focal-plane filter, a dielectric mesa that imparts an additional phase of $\pi/2$ to the central $\sim\lambda/D$ portion of the beam compared to the air path traversed by off-axis rays. When the pupil plane is reimaged, it provides a phase map proportional to $1\pm2\varphi$, where φ is the phase across the input pupil. This literal implementation, with a quarter-wavelength extra phase shift within the central diffraction-limited spot size, is implicitly monochromatic.

A number of basic engineering studies of the feasibility of phase contrast for adaptive optics have been carried out, and the results are promising. We have explicitly considered [6,7] system design for use on PALAO, the Palomar Adaptive Optics system on the 5 m Hale telescope of Palomar Observatory [11,12]. PALAO is a relatively high-order AO system, having 241 active deformable-mirror actuators With its 16x16 visible-light Shack-Hartmann wavefront sensor, PALAO achieves Strehl ratios of up to 70% on bright stars in the near-infrared. It is hoped that the sensitivity advantages of the phase contrast wavefront sensor might permit higher performance still. To achieve broadband operation, our earlier studies considered achromatizing the phase shift of the focal-plane filter through standard multi-layer thin-film design techniques [13], and achromatizing the effective diameter of the phase-shifting spot with auxiliary optics giving a wavelength-dependent transverse magnification [7]. In the next section, we present a novel and very simple alternative approach based on the properties of thin symmetric beam splitters.

3. Achromatization: use of beam splitter phase relationship

It is a remarkable fact that the difference in phase between the beams transmitted and reflected by a thin symmetric beam splitter is $\pi/2$, regardless of wavelength [14,15]. This relationship can serve the needs of the phase contrast filter if these two beams are arranged to be the central, undiffracted rays and the off-axis phase-signal rays discussed in Section 2.

A specific design is presented schematically in Fig. 2. An incident *f/16* beam, representative of that from the Palomar 5 m telescope, strikes a 50:50 beam splitter at a steep angle of incidence, and the reflected and transmitted beams proceed to two mirrors, M1, equidistant from the beam splitter. These flat mirrors direct the beams back to a two-sided mirror, M2, having a diffraction-limited pinhole that passes the central $\sim\lambda/D$ portion of each beam while reflecting the off-axis rays. From each output port, 1 and 2, 50% of the total guide star light emerges, with the requisite $\pi/2$ phase shift between central and off-axis rays. These ports may then be directed into optics that produce a reimaged pupil, and the intensity there will contain the desired phase contrast phase map of the telescope pupil.

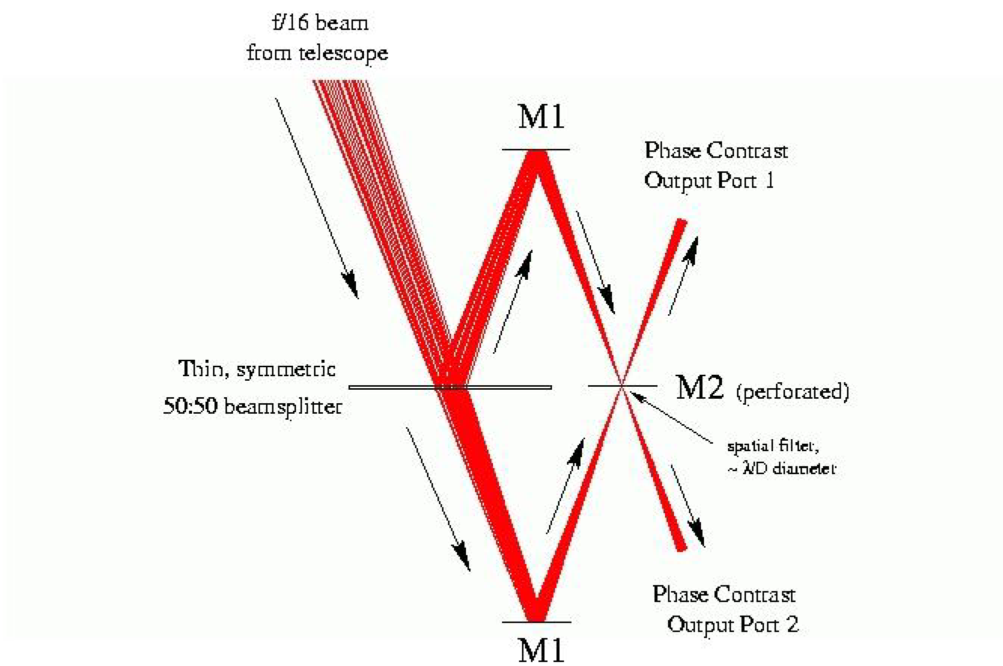

Fig. 2. Schematic broadband implementation of the phase contrast filter as an adaptive optic wavefront sensor, based on the $\pi/2$ phase relationship between transmitted and reflected rays in an ideal beam splitter. The incident beam, converging from the telescope at typically *f/16*, first strikes a 50:50 beam splitter that imparts a $\pi/2$ relative phase shift between transmitted and reflected beams. These beams traverse equal pathlengths to mirror M2, where they come to a focus. A pinhole in M2 transmits the central $\sim\lambda/D$ portion of one beam, while reflecting the outer portion of the other beam (λ is chosen at the center wavelength of the passband: a moderate range of pinhole diameters measured as multiples of different wavelengths may be tolerable, according to simulations, as discussed in the text). The required phase shift between undiffracted central rays and off-axis rays (phase signal) has now been accomplished over a broad spectral band. Each output port nominally contains 50% of the total guide star light, and each provides a map of incident pupil phase proportional to $1\pm2\varphi$.

It appears possible to equalize the number of mirror reflections in the two beams reaching each output port of the wavefront sensor, but this should not be necessary: an extra reflection, as in Fig. 2, should give an achromatic relative phase shift of π between the two paths that won't affect phase contrast operation. It is clearly desirable to utilize both of the output ports shown, as each carries half the phase contrast signal. One simple idea is to direct the outputs onto a single CCD camera from slightly different angles, perhaps with a roof prism. The phase signals in Fig. 2 have opposite signs in the two outputs, so it would be important to combine them after detection. Pre-detection combination in some sort of diplexer would be attractive, and might be feasible if one output signal were inverted with an extra reflection in its path. A potentially more serious consideration is the achromatic nature of the pinhole in mirror M2. In the next section we present numerical simulations indicating that this might not seriously interfere with broadband operation of the wavefront sensor.

4. Simulations of transverse spot size chromaticity

The performance of an ideal phase contrast wavefront sensor was modeled numerically for focal-plane phase-shifting spot diameters of *0.75 λ/D*, *λ/D*, and *1.25 λ/D*; this is equivalent to exploring the response of a single spot size over a commensurate range of wavelengths. The results (Fig. 3) show high-fidelity phase response depending only weakly on wavelength.

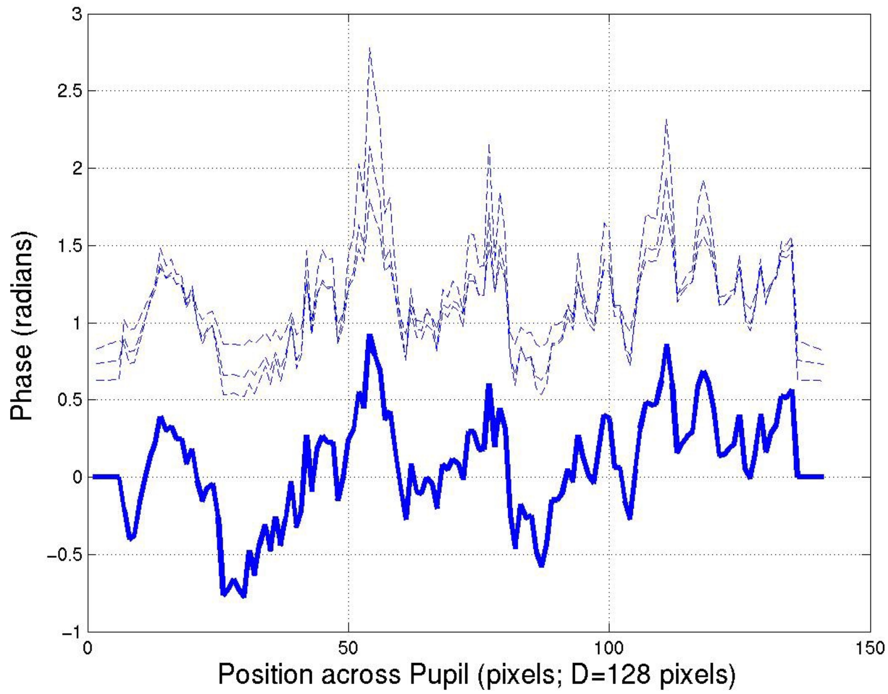

Fig. 3. Simulated response of phase contrast wavefront sensor for a range of wavelengths. The bold curve is a one-dimensional cut through the input phase function $\varphi(\xi,\eta)$, modeled for a wavefront with Strehl ratio $S=0.9$ and DM actuator density $D/a=16$. The three lighter, dashed curves (identically scaled and offset vertically) are wavefront sensor outputs for 3 different choices of the diameter of the focal-plane phase-shifting spot equal to *0.75 λ/D*, *λ/D*, and *1.25 λ/D*, assuming a perfect phase shift of $\pi/2$ in each case. The response is a replica of the input pupil phase, relatively insensitive to the phase-shifting spot diameter in wavelengths, over a wavelength span of 1:1.67, comparable to the optical bandwidth of the current Shack-Hartmann used in the Palomar adaptive optics system. RMS departures of the three outputs from the input are 0.17, 0.10, and 0.16 radians, respectively; RMS input phase variation is 0.36 radians.

The modeled wavefront, having Strehl ratio $S=0.9$ and 16 seeing cells or deformable mirror actuators across the pupil of diameter D (actuator density $D/a=16$), might represent the residual waveform in Palomar's PALAO adaptive optics system once the wavefront has been controlled to a high correction in closed loop. The pupil fields were Fourier transformed to obtain the fields in the intermediate focal plane of Fig. 1; the effects of the Zernike phase contrast phase shifter were computed as a multiplicative mask having a perfect $\pi/2$ phase shift within diameters *0.75 λ/D*, *λ/D*, or *1.25 λ/D*; the fields were inverse Fourier transformed and their squared moduli evaluated to compute intensity in the reimaged pupil.

The response of the phase contrast wavefront sensor at various effective wavelengths agrees well with the common input phase for all three simulations shown in Fig. 3. These preliminary results indicate that the performance of the phase contrast wavefront sensor diagrammed in Fig. 2 might not be severely affected by the chromaticity of the pinhole in mirror M2. (However, if neglecting that chromaticity led to intolerable errors, perhaps for very large bandwidth, the effective pinhole diameter could still be achromatized optically [7].)

There is an additional subtlety generic to direct broadband sensing of phase, rather than phase slopes as in a Shack-Hartmann. A given wavefront distortion in microns of extra optical path length (OPL) produces different phase lags at each wavelength in the passband, in proportion to $1/\lambda$, and so produces different phase contrast signal levels (light intensity levels in the reimaged pupil) that a bolometric wavefront sensor camera would blindly sum. Even so, an accurate DM piston correction for small phase excursions, retaining the signal-to-noise benefits of broad spectral bandwidth, could be derived by using a wavelength-weighted calibration factor. This requires the measured phases to be small, with no wrapping, so they remain linear in differential OPL at all wavelengths. The calibration factor would depend on the color of the guide star, but could be computed in advance knowing that color.

This complication is automatically corrected, though, in a quantum detector such as PALAO's CCD, or any detector with responsivity proportional to λ. The detector then returns a signal proportional to light intensity divided by quantum energy $h\nu$, or essentially to photon count. But the phase contrast intensity is proportional to $(2\pi/\lambda)\cdot$OPL, so the CCD signal is thus directly proportional to the seeing-induced OPL shift, as desired. Different wavelengths may thus be blindly coadded in the detection process without correction or calibration.

5. Conclusions

The phase contrast technique has some natural advantages that make it appealing for real-time adaptive optic wavefront sensing. But to be competitive, a phase contrast wavefront sensor must work over a broad spectral bandwidth. A scheme has been presented in this paper for achieving broadband operation, relying on the simple and fundamental phase relationship existing between reflected and transmitted beams in a thin symmetric beam splitter.

The conditions under which beam splitter phases approach their ideal behavior do not appear unrealistic. The $\pi/2$ phase relationship between reflected and transmitted beams has been shown from very general arguments to hold for a thin symmetric beam splitter, absorbing or not, and is expected to hold for finite-thickness non-absorbing beam splitters, but might not hold for finite-thickness absorbing asymmetric beam splitters [15]. Techniques for fabricating low-loss beam splitters from dielectric materials are well known, and achieving reasonable balance over a broad wavelength range is not difficult. We note that failing to meet perfect 50:50 performance will simply reduce the efficiency of the wavefront sensor.

An illustrative adaptive optics system, Palomar's PALAO, corrects the *f/16* beam from the Cassegrain focus of the 5 m telescope and presents an *f/16* beam to the wavefront sensor. In such a slow beam, the $\sim\lambda/D$ pinhole in the intermediate focal plane shown in Fig. 2 is about 16 wavelengths in diameter, and so diffraction at this spatial filter should not present undue difficulties. Fabrication of a ~16 μm pinhole seems feasible with a photolithographically defined process, though it must be done on a two-sided mirror. The optical scheme in Fig. 2 must be fairly carefully aligned and must maintain its rigidity, if used at visible wavelengths, because the two paths must maintain equal path length to a fraction of a wavelength. The tolerances are equivalent to those of a broadband interferometer holding the white-light fringe, and do not appear excessively difficult to achieve.

A few other practical issues remain to be resolved regarding the use of the phase contrast technique in a real time wavefront sensor for adaptive optics. One is the ease of initially locking a system in strong turbulence: some ideas have been suggested, including bootstrapping onto a Shack-Hartmann [7], which if practical has the additional advantage of simple incorporation into existing AO systems. In any case, the fundamental phase contrast technique appears promising. The ideas presented here offer a way to circumvent one of the most challenging design obstacles, achieving broadband operation easily and inexpensively, without sophisticated thin-film design and fabrication or cumbersome auxiliary optics.

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